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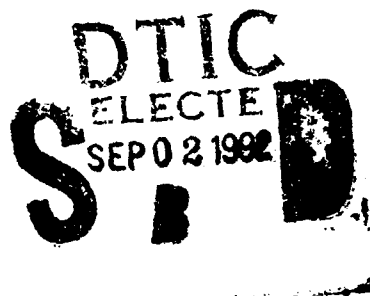
Piloted Evaluation of an Integrated Propulsion and Flight Control Simulator
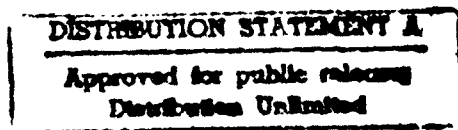
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PILOTED EVALUATION OF AN INTEGRATED PROPULSION AND FLIGHT CONTROL SIMULATOR

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ABSTRACT

This paper describes a piloted evaluation of the integrated flight and propulsion control simulator at NASA Lewis Research Center. The purpose of this evaluation is to demonstrate the suitability and effectiveness of this fixed base simulator for advanced integrated propulsion and airframe control design. The evaluation will cover control effector gains and deadbands, control effectiveness and control authority, and heads up display functionality. For this evaluation the flight simulator is configured for transition flight using an advanced Short Take-Off and Vertical Landing fighter aircraft model, a simplified high-bypass turbofan engine model, fighter cockpit, displays, and pilot effectors. The paper describes the piloted tasks used for rating displays and control effector gains. Pilot comments and simulation results confirm that the display symbology and control gains are very adequate for the transition flight task. Additionally, it is demonstrated that this small-scale, fixed base flight simulator facility can adequately perform a real time, piloted control evaluation.

INTRODUCTION

The Advanced Controls Technology Branch at NASA Lewis is conducting research in the area of integrated flight and propulsion control design, specifically for a Short Take-Off Vertical Landing (STOVL) aircraft. The flight simulator facility was developed to provide a means to validate integrated design methodologies, to monitor engine and airframe parameters during real time simulation, to evaluate new software partitioning methods, and to test control specification bandwidths and control rates through piloted engineering evaluations. This flight simulator has undergone evaluation by certified test pilots for maneuverability, controllability, and

basic functionality to prove that it is a credible, realistic, real-time simulator. This paper describes the evaluation of this flight simulation environment with a brief description of the actual test environment; the control design and physics models used to test the real time capabilities of the simulator; the cockpit effectors and displays used for this evaluation; and the flight scenarios and profiles used for the piloted testing of the flight simulator. Finally, piloted comments and conclusions concerning the suitability of the flight simulator for current research, and recommendations for enhancements are given.

SIMULATION TEST ENVIRONMENT

The flight simulator facility, as shown in Figure 1, consists of an image generation system and UNIX development station, a mockup fighter cockpit, a real time simulation computer, and a control computer system. The image generation system generates the Heads Up Display (HUD), the Heads Down Display (HDD), and the out-the-window scenery using 3 video channels to provide 150 degrees field of view. The fighter cockpit provides pilot effectors for the control of engine and airframe commands. The real time simulation computer executes the real time engine and airframe physics models. Finally, the control computer system executes the integrated control design algorithms. A complete description of this simulation facility is given in reference [1].

For the evaluation of this flight simulator, sample aircraft and engine models, and control designs were selected to test its capabilities. This evaluation had several purposes. First, the minimal heads up and heads down display symbologies required to perform the sample control task were determined. When the flight

simulator configuration could not accommodate the predefined displays as defined in reference [2]; pilot rated, acceptable alternatives that serve the same function were developed. Also, the minimal gains and deadbands for the flight simulator cockpit effectors were determined. In addition, time delays in the simulator response time were measured, and the out the window sceneries were judged for effectiveness during the piloted control task.

CONTROL DESIGN AND PHYSICS MODELS

The vehicle model for this simulation test is a six degree of freedom, delta winged E7-D aircraft with a multi-nozzle turbofan engine shown in Figure 2. The airframe is configured with an ejector nozzle, a ventral nozzle, a 2-dimensional convergent/divergent aft nozzle, and a Reaction Control System (RCS). The RCS allows for control of aircraft attitude during hovering flight. The engine for this aircraft is a mixed flow, vectored-thrust configuration. For this investigation the integrated engine and airframe equations of motion are 14th order with 12 inputs and 10 outputs, and represent a linear, simplified model. Further information about the vehicle, the airframe model, and the engine model can be found in reference [3].

The integrated flight and propulsion controller used for this experiment is a reduced order H-infinity design, which is a linear, 21st order system. The controller includes limiting logic and fan speed scheduling, and is configured only for the transition phase of flight from cruise to hover. A detailed description of the control design is found in references [4,5].

Figure 3 displays a high level view of the discrete linear control design used for this experiment. The pilot inputs from the cockpit effectors are sent to the controller and are scaled by the input effector gradients and prefiltered for command shaping and blending. The prefilter and control blending convert the pilot selections of acceleration, pitch rate, flight path angle, roll rate, and sideslip, into desired velocities, accelerations, and body angles or rates for the controller. The original values for the prefilters were based upon desired handling quality characteristics of the E7-D aircraft during piloted simulations at NASA

Ames Research Center and cockpit configuration tests at General Dynamics, Fort Worth Division. Based on a review of these efforts, it was determined that the NASA Lewis flight simulator could not exactly replicate the implementation of these control effectors. Therefore, the pilot gradients were modified to reflect a displacement control stick, instead of a fixed force sidestick controller as used in the General Dynamics study. The throttle displacement gradients also were modified to reflect linear displacement rather than angular displacement. Further information on the implementation of these control modes for a STOVL task are described in reference [7].

COCKPIT EFFECTORS AND DISPLAYS

Development of the Pilot Vehicle Interfaces (PVI) for this flight simulator was based upon PVI research by Merrick, Farris, and Vanags at NASA Ames Research Center [2]. For demonstration purposes, a STOVL aircraft model, which is described below, was chosen with its associated HUD symbology, HDD instrumentation, and cockpit effector configuration.

The HUD symbology was generated and updated on the visual system development station. The displays and scenery were modified to reflect an integrated engine and airframe control task, typical of a STOVL aircraft. Figure 4 shows an example HUD symbology which was implemented on the flight simulator. The symbology includes a pitch ladder, heading scale, aircraft reference symbol, and flight path symbol. Additionally, engine and aircraft parameters such as altitude, airspeed, forward acceleration, and vertical acceleration rates also are displayed. This symbology was pilot rated during the flight evaluation, and the throttle position and thumbwheel position symbols were added due to pilot preference. A further discussion of the pilot ratings is given in the results section of this paper.

The switches and effectors in the mock-up fighter cockpit are implemented to reflect the simulation of an integrated flight and propulsion control task. The cockpit effectors were based upon a "rate system" command structure. This rate system was implemented to accommodate the three modes of flight that the example STOVL aircraft can encounter: cruise, transition, and

hover. With the rate system commands, the longitudinal stick provides pitch rate/attitude hold; the lateral stick provides roll rate/bank angle hold; the rudder pedals provided sideslip commands; and the linear throttle commands flight path angle.

An additional control effector and a digital switch were added for this simulation -- a rotating thumbwheel and a reset switch. The thumbwheel, positioned on the linear throttle, commands acceleration/deceleration during the transition to hover flight regime. The reset switch, which is normally the trigger switch of the sidestick controller, toggles the simulation between initial condition mode and operate mode. If the simulation reaches saturation limits of the control actuators, the simulation will automatically reset to the initial condition mode. The trigger/reset button places the simulation back into operate mode. A diagram of the cockpit effectors and their functionality is found in Figure 5.

EVALUATION TASKS AND PROCEDURES

To evaluate the control gains and bandwidths for each of the control effectors, the fixed base simulation piloted tasks included the following: (1) straight and level flight to evaluate pitch, (2) straight and level flight to evaluate roll, (3) curved decelerating runway acquisition to evaluate roll and pitch harmony, (4) decelerating approach to runway at various airspeeds to evaluate acceleration/deceleration performance, and (5) decelerating approach to runway and then accelerating to cruise while varying flightpath angle to evaluate flight path response. All scenarios are performed with the aircraft configured for transition phase of flight. The scenarios begin at 1000 feet altitude, 120 knots airspeed in the landing configuration. The aircraft's initial position is changed to either the right or left side of the runway with a 600 foot offset at 4.5 miles away from the final landing point for the curved approaches [6].

The first task was to evaluate the pilot gradients and deadbands associated with the longitudinal control stick. For this evaluation the straight and level flight was performed by the pilot. The sequence of events for this task was to acquire a 5 degree pitch angle, level out, and then

acquire a -5 degree pitch angle. This sequence was increased to 10 degrees pitch and the order of the task was reversed.

The second task was to evaluate the pilot gradients and deadbands associated with the lateral control stick. Straight and level flight also was performed for this test. The sequence of events for this task was to acquire a 10 degree bank angle, level out, and then acquire a -10 degree bank angle. This sequence was increased to 30 degrees bank and the order of the task was reversed.

The next task was to evaluate the pilot gradients and deadbands associated with the lateral and longitudinal stick blending. For this evaluation the curved decelerating runway acquisition task was performed by the pilot. The sequence of events for this task was decelerate at 0.1g along a -3 degree flightpath, then bank right or left to align with the final approach course and maintain airspeed and altitude above the runway. While above the landing site, small pitch and roll adjustments were made to remain aligned with the runway. The initial position of the aircraft was 1000 feet altitude and 4.5 miles from the landing point. For a more difficult tracking task, the distance from the runway was decreased to 3.0 miles and then to 1.5 miles. In this manner, the sharp turning task provided information on the combination of pitch and roll necessary to acquire the runway and maintain alignment.

Another task was to evaluate the pilot gradients and deadbands associated with the thumbwheel controlling acceleration/deceleration. For this evaluation the decelerating approach to the runway at various airspeeds was performed by the pilot. The sequence of events for this task was to acquire a 0.1g rate of deceleration along a -3 degree flightpath, then maintain altitude above the runway at an airspeed of 100 knots, 80 knots, and then 60 knots. This task was repeated for 0.2g deceleration.

The last task was to evaluate the pilot gradients and deadbands associated with the throttle controlling rate of climb or descent. For this evaluation the decelerating approach was performed, followed by the accelerating transition to straight and level flight (wave-off). The

3

sequence of events for this task was to commence a rate of deceleration of 0.1g along a -3 degree flightpath and a -6 degree flightpath, acquire the runway, and maintain airspeed at 80 knots, at 50 feet above the runway. Then, the pilot accelerated to above 95 knots at 0.5 g and then acquired a 3 degree and 5 degree flightpath angle to cruise in conventional flight. This scenario was repeated for a 0.2g deceleration and -6 degree flightpath for a more difficult flightpath control task.

PILOT COMMENTS AND RESULTS

For the pitch control task the pilot found the longitudinal stick responded sluggishly with a considerable time lag between command and aircraft response. This indicated that the deadband of the prefilter was too large for both the small and large pitching task, thus, the deadbands and gains were modified and the tasks were repeated. In this second test the longitudinal stick responded crisply, without much pilot effort for both the small pitching task and the large pitching task in the transition flight mode. The pitch ladder on the HUD responded properly, without noticeable time lag, and the overall rating was good. For this task the original gains and deadbands and the pilot preferred gains for the longitudinal stick appear in figure 6.

For the roll control task the pilot found considerable time lag in the roll response and found that the task required substantial movement in the control effectors. There was no pitch and roll gain harmony between the longitudinal stick and the lateral stick. Various gains and deadbands were tried for the more difficult runway acquisition tasks, but the hardware did not perform adequately, and the pilot continued to make large adjustments to compensate for the poor response of the lateral stick. It was determined at this time that a drift problem existed in the roll axis because the lateral stick had some "slack" and did not always return to center. Due to this problem the minimal deadbands for this control effector were examined.

To resolve the deadband problem in the roll controller, a simple experiment was performed to ascertain when the "slack" in the stick caused a perceptible roll command. During the simulation a small pressure was applied to the roll

controller in each direction of the "slack". The magnitude of the upper and lower deadbands was decreased while the roll command was monitored. Once the roll angle began to drift, the minimum upper deadband was found to be 0.1 inches of deflection, and the minimum lower deadband was found to be 0.06 inches of deflection. The results of this experiment are shown in Figures 7 and 8.

Using this information, the deadbands were set to this minimal "drift limit", and the roll control task and the curved decelerating runway acquisition tasks were repeated to evaluate the lateral control stick performance and the pitch/roll gain harmony. The original gains and the improved effector gains are given in figure 9. These gains reflect good pitch and roll harmony, good handling qualities of the control effectors for this task, and appropriate operation of the heads up display symbology. Additionally, the 150 degrees field of view scenery was a large improvement over the original single channel system and was a necessary expansion in order to perform the runway acquisition task.

The next task to evaluate acceleration/deceleration originally had been implemented using the throttle effector in the General Dynamics study.[7] Due to pilot preference, this study concluded that the thumbwheel should control acceleration/deceleration. Because of this new implementation, the thumbwheel gains were scaled to reflect the change in effectors. Initially, this effector was also difficult to accurately evaluate because there was no detent to show null position, and the thumbwheel could rotate 270 degrees. This was not acceptable for this evaluation, therefore, the rotation was limited to 36 degrees. (approximately the span one's thumb could move in a single motion). Also, no other hardware modifications could be made on this effector because it will serve a different function in the cruise and hover modes, therefore, a heads up display symbology was used to show thumbwheel position. (please refer to figure 4.)

Once these modifications in hardware were implemented, the precision task of decelerating to the runway was evaluated. The pilot found the scaled thumbwheel gains were very crisp and the symbology responded very sharply.

Consequently, the original gains were altered only to reflect the 36 degree rotation limit and the scaling due to the change in implementation. These gains appear in figure 10.

The final evaluation was of the throttle effector. The throttle had originally controlled acceleration/deceleration, however, the pilot preferred to control rate of descent with this effector. Because of this new implementation, the throttle gains were scaled to reflect the change in effectors. Initially, this effector was also difficult to accurately evaluate because there was no detent. The heads up display, once again, provided information to display throttle position. Once this was implemented, the tasks of decelerating to the runway and accelerating to cruise were performed. The pilot found the throttle response was very crisp, with no response delays in the flightpath symbol. The original gains and the new gains used for this task are presented in figure 11.

The rudder pedals gradients and deadbands were not evaluated because of their limited use during the transition case scenarios, however, they were evaluated to show proper functionality and response to pilot commands. The default pilot gradients used for this evaluation are given in figure 12.

CONCLUSIONS

The integrated propulsion and flight simulator has successfully been designed, built, and demonstrated as a real time, pilot-in-the-loop, evaluation station for integrated engine and airframe control laws. The flight simulator performed very adequately in the piloted ratings for the fixed base simulation of a Short Take-Off Vertical Landing aircraft during the transition to hover phase of flight. Control effector gradients, deadbands, and heads up display symbologies were evaluated by the pilot. The flight simulator was configured to reflect pilot preferences of the control effectors and displays. Piloted ratings show that this fixed base flight simulator configuration, with its associated control effector gradients, gains, and displays, can be used to adequately evaluate integrated flight and propulsion control laws in transition to hover scenarios. As a further demonstration of this simulator's capability, a full

control evaluation of the transition to hover case scenario will be performed on the fully nonlinear STOVL aircraft model, engine model, and complete control design.

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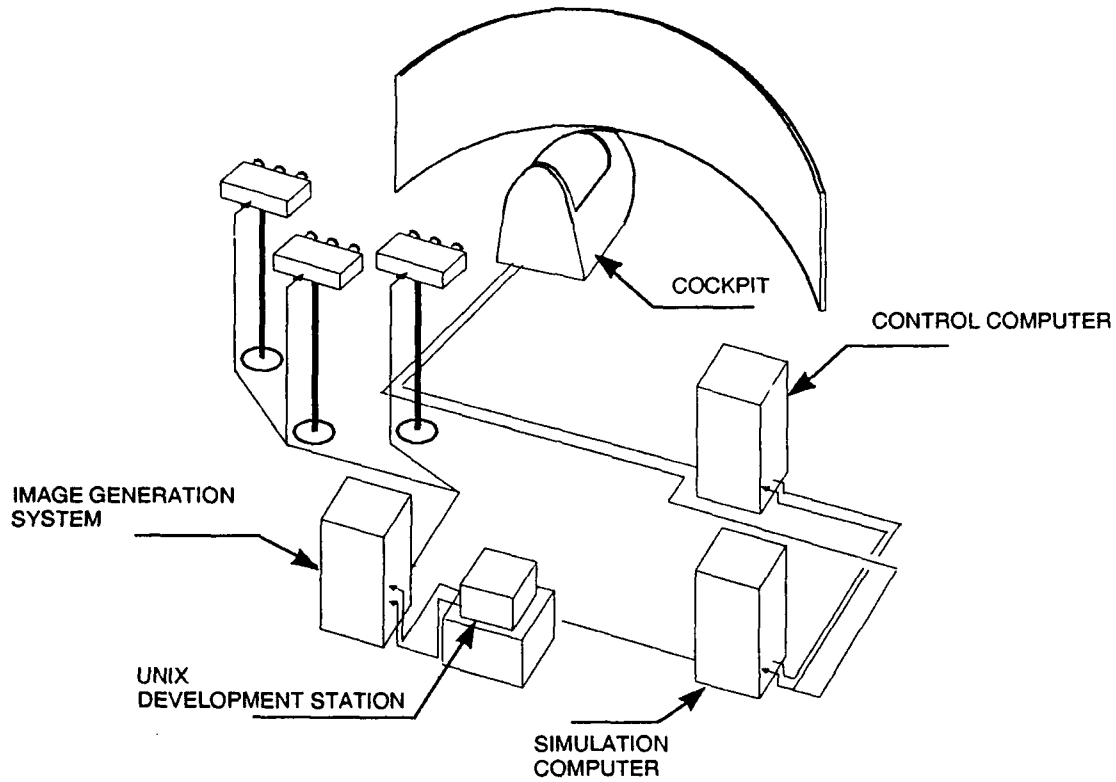
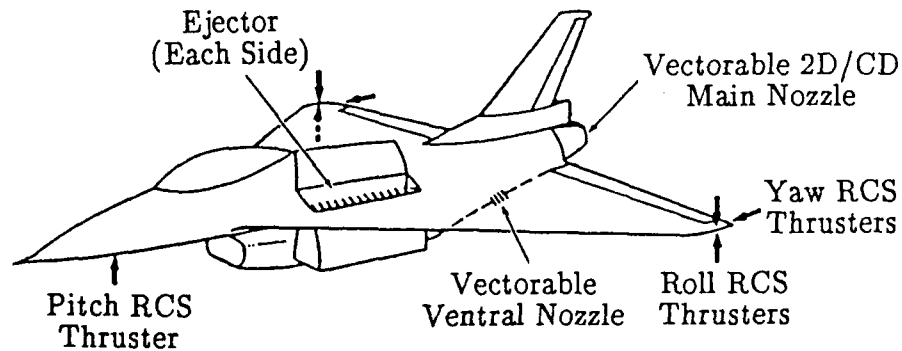Figure 1. Flight Simulator Facility
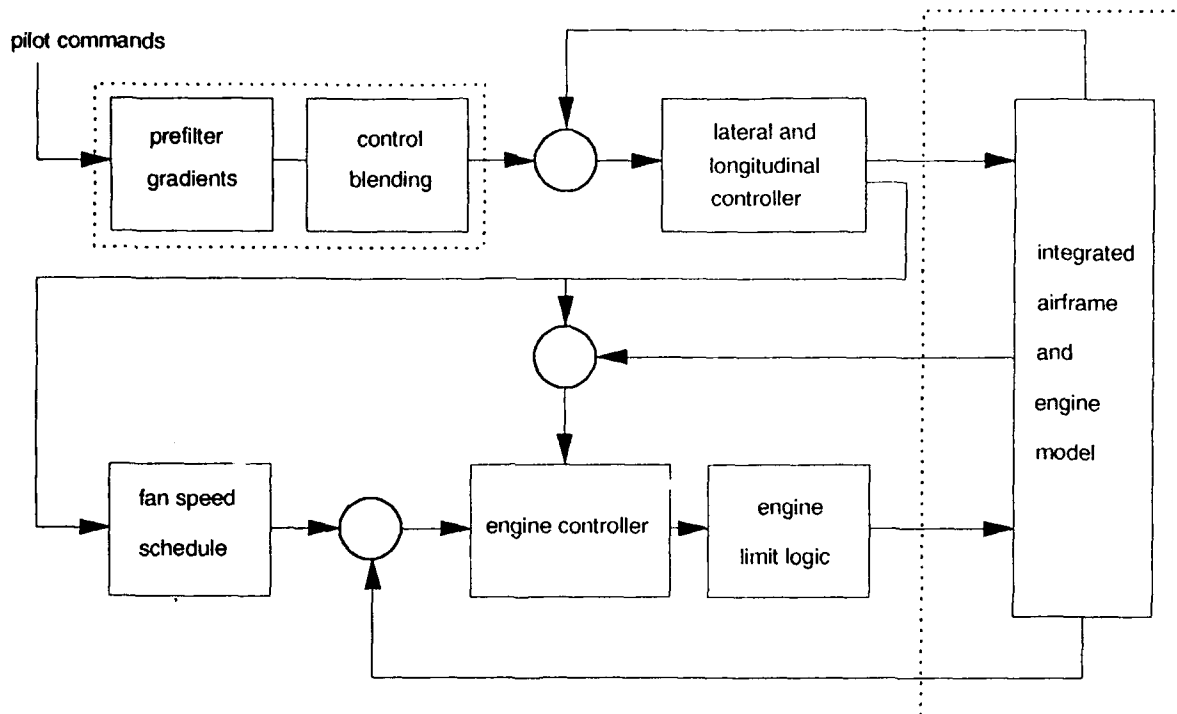
Figure 2. E7-D Aircraft Model
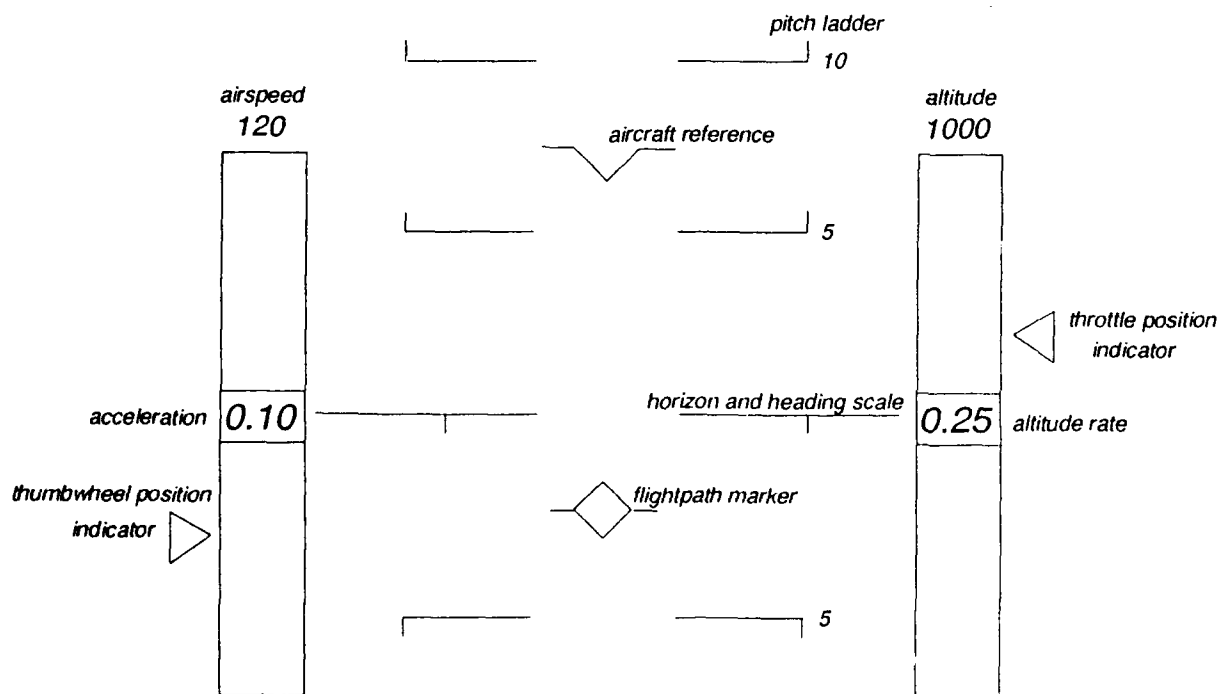
Figure 3. Block Diagram of Transition Control Design

Figure 4. Heads Up Display Symbology for Transition Flight

pilot command \ control inceptor	Throttle	Thumb Wheel	Longitudinal Stick	Lateral Stick	Rudder Pedals
accel/decel		X			
flightpath angle	X				
rollrate				X	
pitchrate			X		
sideslip					X

THROTTLE   SIDESTICK

thumbwheel

reset switch
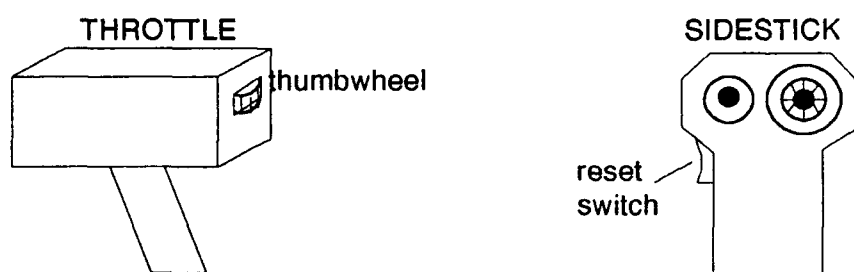
Figure 5. Cockpit Effectors in Transition Flight Mode
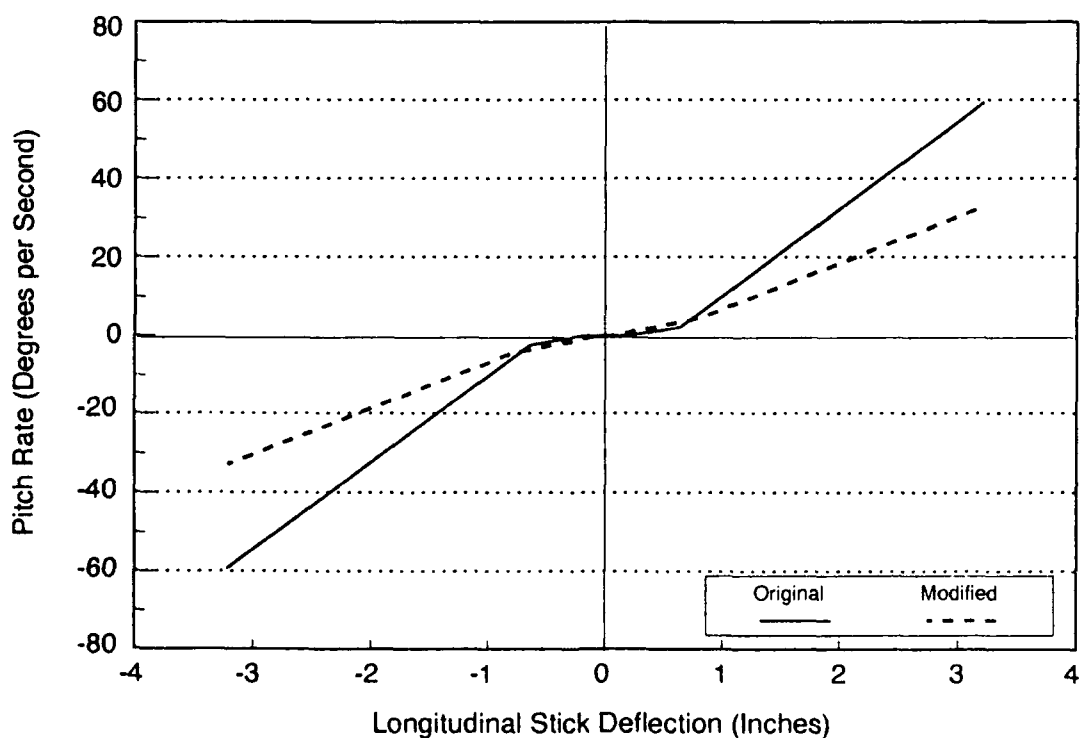
Figure 6. Longitudinal Stick Gain and Deadband
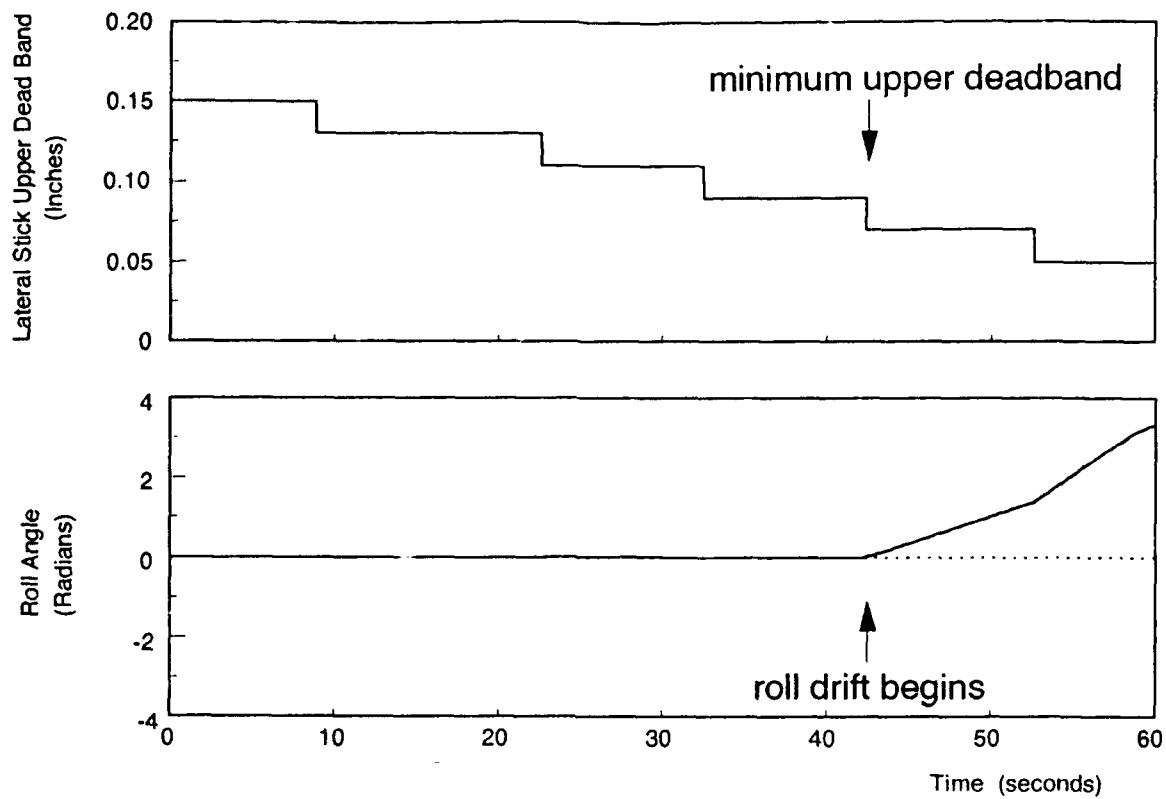
Figure 7. Upper Deadband for Lateral Stick
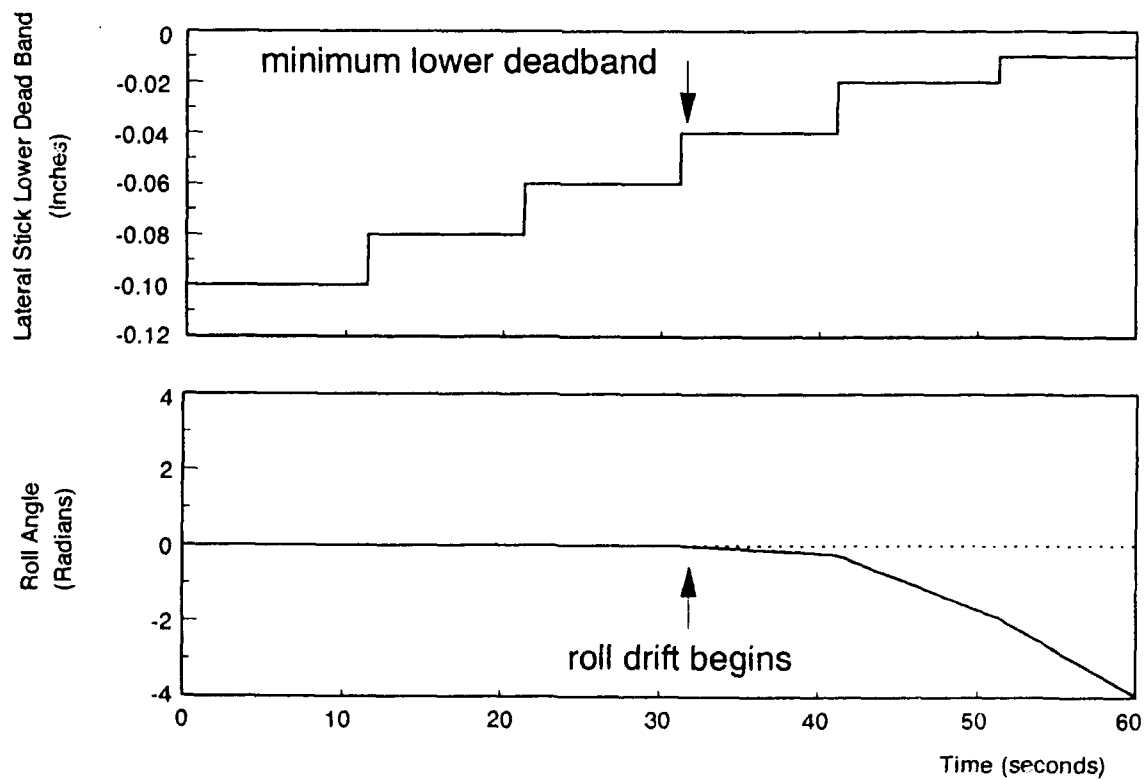
Figure 8. Lower Deadband for Lateral Stick

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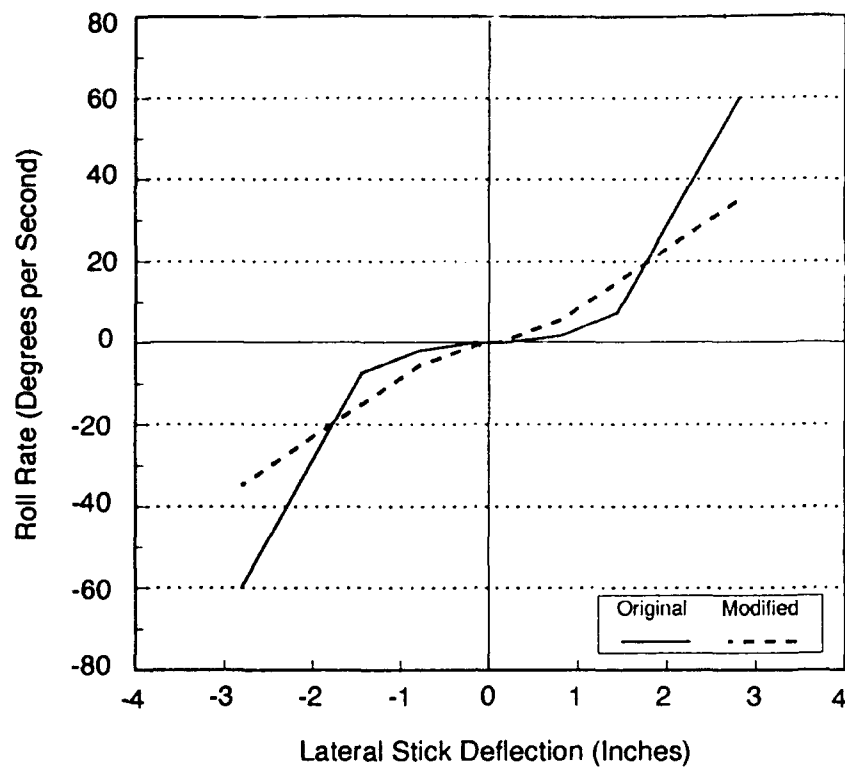
Figure 9. Lateral Stick Gain and Deadband
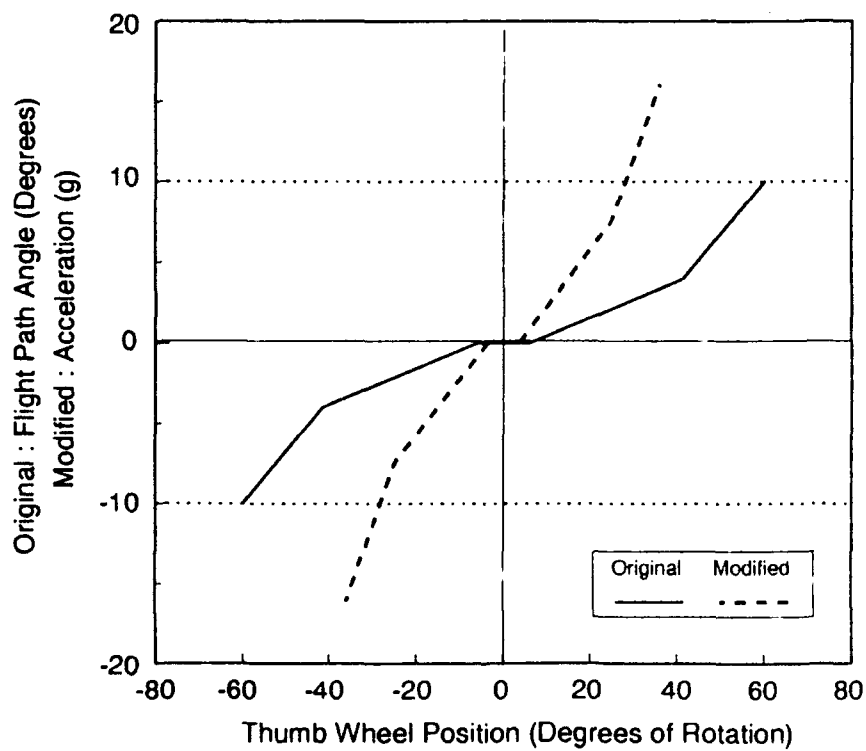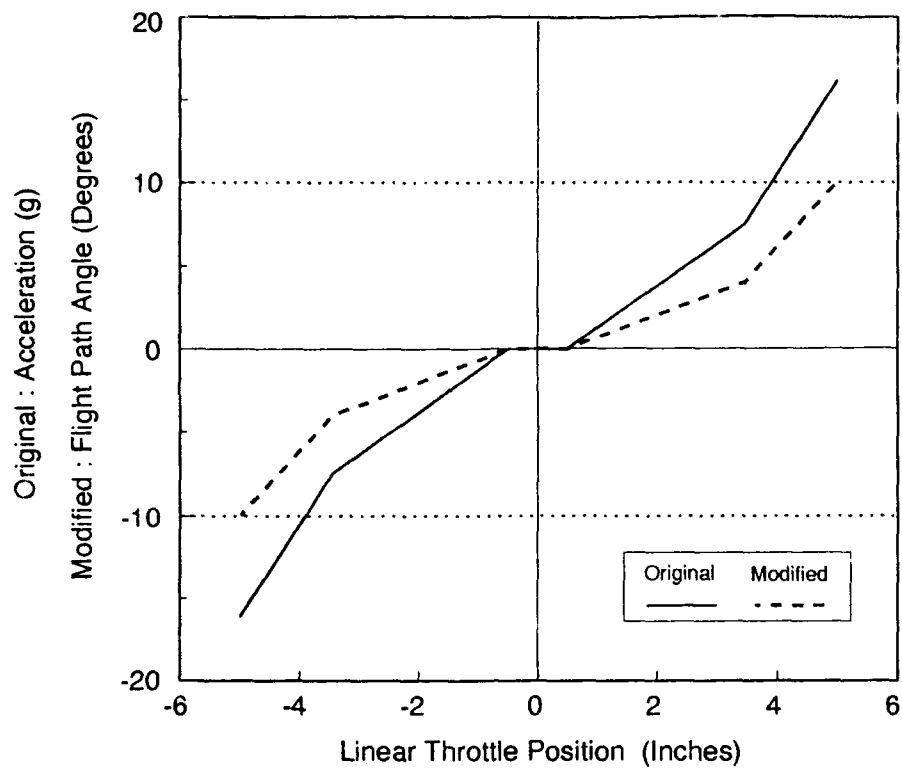

Figure 10. Rotating Thumb Wheel Gain and Deadband
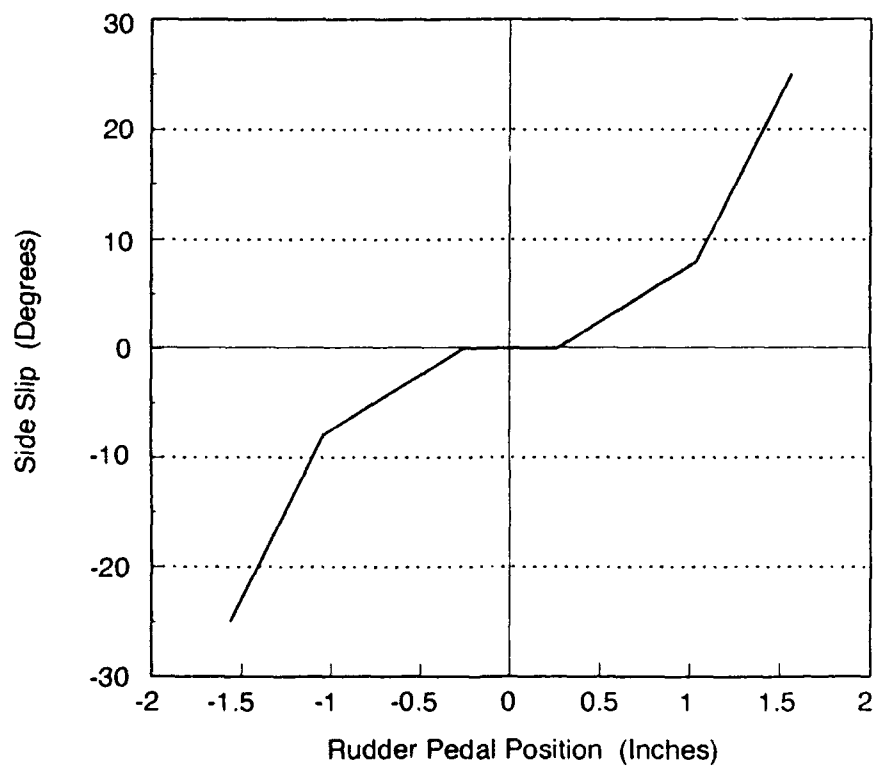
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Figure 11. Linear Throttle Gain and Deadband

Figure 12. Rudder Pedal Gain and Deadband

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12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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14. SUBJECT TERMS

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